

# Two-nucleon knockout contributions to the $^{12}\text{C}(e, e'p)$ reaction in the dip and $\Delta(1232)$ regions

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## Abstract

The contributions from  $^{12}\text{C}(e, e'pn)$  and  $^{12}\text{C}(e, e'pp)$  to the semi-exclusive  $^{12}\text{C}(e, e'p)$  cross section have been calculated in an unfactorized model for two-nucleon emission. We assume direct two-nucleon knockout after virtual photon coupling with the two-body pion-exchange currents in the target nucleus. Results are presented at several kinematical conditions in the dip and  $\Delta(1232)$  regions. The calculated two-nucleon knockout strength is observed to account for a large fraction of the measured  $(e, e'p)$  strength above the two-nucleon emission threshold.

Rosenbluth separations of the inclusive electron scattering ( $e, e'$ ) cross section have established the predominant transverse nature of the strength in the dip region between the quasielastic and  $\Delta(1232)$  peaks [1]. Whereas the quasielastic and  $\Delta(1232)$  peaks have been the subject of an extensive theoretical activity, the physics of the dip region is less explored and relatively badly understood. In a Fermi-gas model calculation, Van Orden and Donnelly have shown that meson-exchange currents (MEC) can make up for a significant part of measured inclusive strength in the dip region [2]. Recently, the Fermi-gas calculations have been readdressed by Dekker, Brussaard and Tjon in a fully relativistic framework [3]. They find a substantially larger ( $e, e'$ ) response for energy transfers above the quasielastic peak than Van Orden and Donnelly, an effect which they attribute to their non-static treatment of the  $\Delta$  current operator. The predominance of the MEC was confirmed in the semi-phenomenological quasi-deuteron calculations for  $^{12}\text{C}(e, e')$  by Laget and Chrétiens-Marquet [1]. Although the quasi-deuteron and the recent Fermi-gas results look promising, a complete microscopic description of the inclusive electron scattering data in the dip region is still lacking. Given the important role attributed to MEC, it has been suggested that two-nucleon knockout may account for a significant part of the strength [4]. Above the pion-production threshold, also quasi-free pion production via intermediate  $\Delta(1232)$  excitation is a significant source of ( $e, e'$ ) strength [1].

More detailed information about the various reaction mechanisms is supposed to be gained from coincidence experiments. The first ( $e, e'p$ ) measurement in the dip region was reported by Lourie et al. [5]. The attained  $^{12}\text{C}(e, e'p)$  spectrum is characterized by peaks corresponding to knockout from the  $1p$  and  $1s$  shell and by a significant and almost uniform continuum strength extending to high missing energies  $E_m = \omega - T_p$ . Here,  $\omega$  is the transferred energy in the electron-scattering process and  $T_p$  is the measured proton kinetic energy. The results of the investigations reported in ref. [5] thus exclude a purely one-body knockout character of the ( $e, e'p$ ) reaction process in the dip region. Similar observations were made in the subsequent  $^{12}\text{C}(e, e'p)$  measurements of Baghaei et al. [6] probing the nuclear response in the  $\Delta$ -resonance region. Here, the  $E_m$  dependence of the proton strength is characterized

by a strong enhancement above the pion production threshold.

The effect of the final-state interaction (FSI) on the continuum part of the  $(e, e'p)$  spectra was investigated by Takaki [7,8]. He concluded that FSI effects following virtual photon coupling with a one-body current does neither qualitatively nor quantitatively account for the data of ref. [5]. Based on the results of calculations performed with a simple model for two- and three-nucleon absorption he argued further that a reaction mechanism in which the virtual photon couples with the two-body currents may dominate the  $(e, e'p)$  cross sections for the missing energy region right above the two-nucleon emission threshold. Such a reaction mechanism, however, was found to generate relatively little strength at higher missing energies. In order to account for the observed  $(e, e'p)$  strength at high missing energies, Takaki invoked three- and more-nucleon processes.

Here, we report on a calculation of the two-nucleon knockout contribution to the semi-exclusive  $^{12}\text{C}(e, e'p)$  reaction in the dip and  $\Delta(1232)$  regions and compare the results with earlier measurements from MIT-Bates and new data taken at NIKHEF-K. The latter represent the first semi-exclusive  $(e, e'p)$  data for a complex nucleus taken in non-parallel kinematics. All MIT-Bates measurements in the dip and  $\Delta$  regions are performed in parallel kinematics, i.e. the proton is detected along the direction of the transferred momentum  $\mathbf{q}$ .

The two-nucleon knockout contribution to the semi-exclusive  $(e, e'p)$  channel is determined by integrating the  $(e, e'pp)$  and  $(e, e'pn)$  cross sections over the solid angle of the undetected hadron :

$$\begin{aligned} \frac{d^6\sigma}{dE_p d\Omega_p d\epsilon' d\Omega_{\epsilon'}}(e, e'p) = & \sum_f \int d\Omega_{p'} \frac{d^8\sigma}{dE_p d\Omega_p d\Omega_{p'} d\epsilon' d\Omega_{\epsilon'}}(e, e'pp) \\ & + \sum_f \int d\Omega_n \frac{d^8\sigma}{dE_p d\Omega_p d\Omega_n d\epsilon' d\Omega_{\epsilon'}}(e, e'pn) , \end{aligned} \quad (1)$$

where the sum over  $f$  extends over all final states of the residual (A-2) system. Here, it is assumed that the two-hadron knockout process is the result of a direct knockout (DKO) mechanism after virtual photon absorption on a correlated nucleon pair in the target nucleus (fig. 1). This means that the photoabsorption mechanism involves two active nucleons. The term “correlations” is defined here in its most general sense, referring to any type of

mutual interaction two nucleons experience when embedded in a nuclear medium. The calculations presented here are restricted to rather moderate momentum transfers  $q$  and therefore one may assume that the nucleon-nucleon correlations are dominated by one-pion exchange mechanisms. As illustrated in fig. 1 we consider all diagrams with one exchanged pion retaining both the non-resonant (fig. 1(a) and 1(b)) and resonant (fig. 1(c)) terms. Accordingly, in the calculation of the  $(e, e'NN)$  cross sections the virtual photon is taken to couple exclusively with a transverse two-body current. This means that we discard all longitudinal contributions to the  $(e, e'NN)$  cross sections. The longitudinal strength can be expected to be dominated by the short-range correlations [9] and multi-step processes [8]. Given that the  $(e, e')$  strength has a predominantly transverse nature in the dip and  $\Delta$  regions, one may infer that the two-body currents of fig. 1 are responsible for a large fraction of the  $(e, e'p)$  strength.

Following standard procedures the coincidence differential cross section for the  $A(e, e'NN)A-2$  process in the laboratory frame can be written as :

$$\frac{d^8\sigma}{dE_b d\Omega_b d\Omega_a d\epsilon' d\Omega_{\epsilon'}}(e, e'N_a N_b) = \frac{1}{4(2\pi)^8} k_a k_b E_a E_b f_{rec} \sigma_M [v_T W_T + v_S W_{TT}] , \quad (2)$$

where  $\sigma_M$  is the Mott cross section and  $f_{rec}$  a recoil factor. The electron kinematical factors are given by  $v_T = tg^{2\frac{\theta_e}{2}} - \frac{q_\mu^2}{2q^2}$  and  $v_S = \frac{q_\mu^2}{2q^2}$ . Notation conventions for the kinematical variables are summarized in fig. 1. The structure functions  $W$  are defined in terms of the transition matrix elements  $m_{fi}$  of the transverse two-body current operator :

$$W_T = |m_{fi}(\lambda = +1)|^2 + |m_{fi}(\lambda = -1)|^2$$

$$W_{TT} = 2Re [(m_{fi}(\lambda = +1)) (m_{fi}(\lambda = -1))^*] , \quad (3)$$

and constitute the essential quantities to be calculated. Remark that eq. (2) has been derived under the assumption that electro-induced two-nucleon ejection is a purely transverse process. For the reactions under consideration where two hadrons characterized by the momentum/spin variables  $(\mathbf{k}_a, m_{s_a})$  and  $(\mathbf{k}_b, m_{s_b})$  are ejected, the transition matrix element reads :

$$m_{fi}(\lambda) = \left\langle \mathbf{k}_a \frac{1}{2} m_{s_a}; \mathbf{k}_b \frac{1}{2} m_{s_b}; J_R M_R (A-2) \left| J_\lambda^{[2]}(q) \right| g.s.(A) \right\rangle \quad (\lambda = \pm 1), \quad (4)$$

with  $J_\lambda^{[2]}$  the Fourier transformed nuclear two-body current. In the evaluation of the diagrams 1(a) and 1(b) we employ the non-relativistic reduction of the current operators that correspond with the one-pion exchange potential. They are derived from the pseudovector  $\pi NN$  coupling Lagrangian [2,10]. The non-static  $\Delta$  current operator we use in our investigations is :

$$\begin{aligned} \mathbf{J}^{(\pi\Delta)}(\mathbf{q}; \mathbf{k}_1, \mathbf{k}_2) = & \frac{2if_{\gamma N\Delta}f_{\pi N\Delta}f_{\pi NN}}{9m_\pi^3(M_\Delta - M_N - \omega - \frac{i}{2}\Gamma_\Delta(\omega))} \left\{ \left[ -(\boldsymbol{\tau}_1 \times \boldsymbol{\tau}_2)_z \frac{\boldsymbol{\sigma}_2 \cdot \mathbf{k}_2}{k_2^2 + m_\pi^2} (\boldsymbol{\sigma}_1 \times \mathbf{k}_2) \times \mathbf{q} + \right. \right. \\ & \left. \left. + 4(\boldsymbol{\tau}_2)_z \frac{\boldsymbol{\sigma}_2 \cdot \mathbf{k}_2}{k_2^2 + m_\pi^2} (\mathbf{k}_2 \times \mathbf{q}) \right] + 1 \longleftrightarrow 2 \right\}, \end{aligned} \quad (5)$$

which corresponds with the non-relativistic reduction of the  $\Delta$  current operator as derived in ref. [3]. The  $\Delta$ -width  $\Gamma_\Delta(\omega)$  was taken according to the parametrization of Oset, Toki and Weise [11]. The various coupling constants are  $\frac{f_{\pi NN}^2}{4\pi}=0.079$ ,  $\frac{f_{\pi N\Delta}^2}{4\pi}=0.37$  and  $f_{\gamma N\Delta}^2=0.014$ . For the electromagnetic formfactors the standard dipole form is adopted. For the strong  $\pi NN$  and  $\pi N\Delta$  formfactor a monopole form  $(\Lambda_\pi^2 - m_\pi^2)/(\Lambda_\pi^2 + \mathbf{k}^2)$  with a cut-off mass  $\Lambda_\pi$  fixed at 1200 MeV was used.

In order to account for the distortions that the escaping nucleons undergo through the interaction with the (A-2) spectator nucleons a technique based on a partial wave expansion for the wave function of each of the escaping particles has been developed. This procedure is a natural extension of the shell-model approach to one-nucleon knockout reactions [12]. Essentially, the final antisymmetrized state with two escaping nucleons having momenta  $\mathbf{k}_a$  and  $\mathbf{k}_b$  is obtained by performing an expansion in terms of two-particle two-hole ( $2p - 2h$ ) eigenfunctions of a mean-field potential. More details can be found elsewhere [13]. Since the final state is expressed in coordinate space, the integrations over the solid angle of the undetected hadron in eq. (1) can be performed analytically, thus keeping the numerical calculations feasible. A similar procedure as the one sketched here for the semi-exclusive ( $e, e'p$ ) reaction has been worked out in more detail for the semi-exclusive ( $\gamma, p$ ) reaction in ref. [14]. In the context of ( $\gamma, NN$ ) reactions, the two-nucleon emission model adopted here

has been shown to give a fair account of the absolute  $^{16}\text{O}(\gamma, pn)$  and  $^{16}\text{O}(\gamma, pp)$  angular cross section data [14].

In the  $^{12}\text{C}(e, e'p)$  calculations all possible contributions from the removal of proton-neutron and proton-proton pairs in the  $(1p_{3/2})^2$ ,  $(1p_{3/2}, 1s_{1/2})$  and  $(1s_{1/2})^2$  shell-model configurations are included. The single-particle wave functions and scattering phase shifts entering the matrix elements are obtained from a Hartree-Fock calculation with an effective Skyrme type of interaction. Within the adopted model assumptions, the residual nucleus is created in a  $2h$  configuration  $| (hh')^{-2} >$  relative to the ground state of the target nucleus. Therefore, all spectroscopic information in the calculations is contained in the two-hole spectral function  $S_{hh'}$ . The  $S_{hh'}(E_x)$  determines the distribution of the  $| (hh')^{-2} >$  strength as a function of the excitation energy  $E_x$  in the  $(A-2)$  nucleus. This distribution was parametrized according to [14] :

$$S_{hh'}(E) = \int_0^E S_h(E') S_{h'}(E - E') dE' . \quad (6)$$

The single-hole spectral functions  $S_h(E)$  occurring in this expression are taken from ref. [15].

In fig. 2 we present the calculated  $^{12}\text{C}(e, e'pp)$  and  $^{12}\text{C}(e, e'pn)$  contributions to the semi-exclusive  $^{12}\text{C}(e, e'p)$  channel as a function of the missing energy at different values of the proton angle  $\theta_p$ . ( $-180^\circ \leq \theta_p \leq 180^\circ$ ). The proton scattering angle  $\theta_p$  is expressed relative to the direction of  $\mathbf{q}$ . Since the  $(e, e'NN)$  reaction is a purely transverse process within the adopted model assumptions, the azimuthal dependence of the calculated semi-exclusive cross sections is solely determined by  $\cos(2\varphi_p)$ . All forthcoming considerations are for in-plane kinematics ( $\varphi_p = 0^\circ, 180^\circ$ ). Accordingly, the angular dependence of the calculated cross sections is uniquely determined by the absolute proton angle  $|\theta_p|$ . The electron kinematics of fig. 2 are taken from a recent experiment performed at NIKHEF-K and are typical for the dip region [16]. For these kinematics, the numerical calculations predict the two-hadron emission strength to sharply rise above the threshold and to be spread over a wide range of missing energies. The calculated missing energy spectra show a clear dependence on  $\theta_p$ . The  $E_m$  strength distribution, which has a clear bump structure in parallel kinematics ( $\theta_p = 0^\circ$ ),

exhibits a wider structure with increasing proton detection angle  $|\theta_p|$ . In conformity with the conclusions drawn by Takaki, our calculations suggest that in parallel kinematics a uniform  $(e, e'p)$  strength distribution extending over a wide  $E_m$  range is incompatible with two-nucleon knockout as the sole contributing channel.

Inspecting fig. 2 it is clear that the  $pp$  and  $pn$  contributions show a slightly different functional dependence on  $\theta_p$ . The  $pp$  part decreases more rapidly with increasing  $\theta_p$  than the  $pn$  part. This property is reflected in the  $(e, e'pn)$  to  $(e, e'pp)$  ratio which is less than ten in parallel kinematics and steadily grows as the proton is detected at larger angles  $|\theta_p|$ .

The calculated cross sections have been compared with the results of  $^{12}\text{C}(e, e'p)$  experiments recently performed at NIKHEF-K and earlier measurements by Baghaei *et al.* [6]. The measurements at NIKHEF were performed at two sets of values for the energy and momentum transfer, one in the dip region ( $\omega=212$  MeV,  $q=270$  MeV/c) and the other one at the rising slope of the  $\Delta$ -resonance peak ( $\omega=263$  MeV,  $q=303$  MeV/c). Here, only a selection of the NIKHEF data is shown. An in-depth comparison of the predictions shown in fig. 2 and the NIKHEF data at  $\omega=212$  MeV, which include missing-energy spectra at various proton angles, will be presented elsewhere [16]. Summarizing, for the kinematical conditions of fig. 2 the calculations essentially reproduce the data for  $|\theta_p| \geq 74^\circ$  and underestimate the data by about a factor of two at smaller values of  $|\theta_p|$ . In figs. 3 and 4 the calculated  $E_m$  spectra are compared with the data which are representative for the low-energy side of the  $\Delta(1232)$  resonance peak. For both data sets the transferred energy  $\omega \approx 270$  MeV. The MIT-Bates results of fig. 4 were taken at slightly larger momentum transfer ( $q=401$  MeV/c) than the NIKHEF-K data of fig. 3 ( $q=303$  MeV/c). The combined data sets cover a range of proton angles from  $|\theta_p| = 0^\circ$  up to  $|\theta_p| = 113^\circ$ . Generally, a reasonable description of the low  $E_m$  part of the  $^{12}\text{C}(e, e'p)$  spectra is achieved. For  $\theta_p = 0^\circ$  and  $38^\circ$  the theory clearly falls short of accounting for the measured strength at high  $E_m$ . This is expected since the model does not include the real-pion production channels. As the mismatch between  $\mathbf{q}$  and  $\mathbf{k}_p$  is large, pion electroproduction  $(e, e'p\pi^-)$  is not expected to



contribute substantially to the proton spectra at large  $\theta'_p$ s. As such, the backward proton angles are best suited to study the two-nucleon knockout contribution to the semi-exclusive processes. It is precisely for  $\theta_p = 113^\circ$  that we arrive at a fair description of both the  $E_m$  dependence and the magnitude of the data. Therefore, it is tempting to conclude that at the backward angles the semi-exclusive cross sections are dominated by two-nucleon knockout caused by MEC and  $\Delta$  currents. Remark further that the calculated missing-energy spectra of figs. 3 and 4 show a functional dependence on  $\theta_p$  similar to the curves of fig. 2 which are obtained at a lower  $\omega$ .

Summarizing, the  $(e, e'pp)$  and  $(e, e'pn)$  contribution to the semi-exclusive  $^{12}\text{C}(e, e'p)$  process in the dip and  $\Delta$  regions has been computed using a mean-field approximation to account for the distortions that the ejected hadrons undergo. The electro-induced two-hadron emission processes are assumed to be caused by a direct knockout mechanism following electron scattering off the two-body pion-exchange and  $\Delta$  currents in the target nucleus. The overall shape of the calculated  $^{12}\text{C}(e, e'p)$  missing energy spectra is found to be dependent on the proton emission angle  $\theta_p$  and as such measurements of the  $(e, e'p)$  spectra at several values of  $\theta_p$  are well suited to provide a deeper insight into the relative importance of the two-nucleon knockout contributions. The presented model, which is parameter-free, works reasonably well in reproducing that part of the  $^{12}\text{C}(e, e'p)$  missing energy spectra which resides below the pion production threshold. Consequently, two-hadron knockout is found to be a substantial contribution to the  $(e, e')$  reaction mechanism above the quasielastic peak. We believe that semi-exclusive  $(e, e'p)$  reactions constitute an important tool in the study of electro-induced two-hadron knockout processes and provide a direct way of gaining deeper insight into the nature of nucleon-nucleon correlations in finite nuclei.

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## FIGURES

FIG. 1. Schematic representation of an electro-induced two-nucleon ejection process in a direct knockout picture. Also the different types of nucleon-nucleon correlations retained in the calculations are shown : (a) Seagull, (b) pion-in-flight and (c)  $\Delta$ -resonance diagrams.

FIG. 2. Theoretical missing-energy spectrum of the  $^{12}\text{C}(e, e'p)$  process at  $\epsilon=475$  MeV,  $\omega=212$  MeV and  $q=270$  MeV/c. The calculated contribution from  $(e, e'pn)$  (top) and  $(e, e'pp)$  (bottom) is shown for  $\theta_p=0^\circ$  (solid curve),  $\theta_p=60^\circ$  (dotted curve),  $\theta_p=120^\circ$  (dot-dashed curve) and  $\theta_p=180^\circ$  (dashed curve).

FIG. 3. Missing-energy spectrum of the  $^{12}\text{C}(e, e'p)$  process at  $\epsilon=478$  MeV,  $\omega=263$  MeV and  $q=303$  MeV/c. The dashed (dotted) curve shows the calculated  $(e, e'pn)$  ( $(e, e'pp)$ ) contribution, the solid curve their incoherent sum. The arrow indicates the threshold for the  $(e, e'p\pi^-)$  channel.

FIG. 4. As in fig. 3 but at  $\epsilon=460$  MeV,  $\omega=275$  MeV and  $q=401$  MeV/c. The data are from ref. [6].

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